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The Use of Neuromuscular Electrical Stimulation in the Gait Training of Children with Cerebral Palsy: A Literature Review

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THE USE OF NEUROMUSCULAR ELECTRICAL STIMULATION IN THE GAIT TRAINING OF CHILDREN WITH CEREBRAL PALSY: A LITERATURE REVIEW

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This Independent Study, submitted by Rachel A. Rolfson in partial fulfillment of the requirements for the Degree of Master of Physical Therapy from the University of North Dakota, has been read by the Faculty Preceptor, Advisor, and Chairperson of Physical Therapy under whom the work has been done and is hereby approved.

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Signature Rachel Royson

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ABSTRACT

Cerebral palsy is a common developmental disorder that causes a wide array of problems in the population. The manifestations of cerebral palsy commonly interfere with the child's activities of daily living, including the important function of gait. It is therefore important that physical therapists be knowledgeable about the various treatment options used in gait training of children with cerebral palsy, as well as their effectiveness.

Neurodevelopmental techniques (NDT), neurosurgical interventions, and orthotics are just a few of the numerous treatment options available for the gait training of children with cerebral palsy. Neuromuscular Electrical Stimulation (NMES) has recently become a popular method used to improve the child with cerebral palsy's gait pattern, however the use of NMES, and more specifically its effectiveness, is controversial.

The purpose of this literature review is to discuss the theoretical foundations supporting NMES, the mechanism behind NMES, and the various forms and effects of NMES, and its use in the gait training of children with cerebral palsy.

Through the review of current literature, NMES was found to be an effective method of improving gait function in children with cerebral palsy.

CHAPTER I

INTRODUCTION

Tecklin[1] describes cerebral palsy (CP) as "... not a disease, but is, rather, a category of disability including patients with one kind of problem: chronic non-progressive disorders of movement or posture of early onset.[1] The anatomic sites of involvement, degree of motor disability, associated dysfunctions and cause are heterogeneous." Consequently, pediatric physical therapists involved in the treatment of children with CP are faced with a variety of different movement or posture disturbances.

Despite the advancements being made in neonatal care, CP effects 2 in 1000 live births.[2] In fact, the National Collaborative Perinatal Project projects the numbers to be as high as 5.2:1000 live births.[1] These numbers make CP one the most common developmental disorders affecting the pediatric population today.[3] Therefore, it is important that physical therapists be knowledgeable about the various treatment options used with children who have been diagnosed with CP, as well as their effectiveness.

Children with CP have problems with gait due to varying degrees of loss of voluntary muscle control, dependence on immature reflex patterns for walking, abnormal muscle tone, relative imbalance between muscle agonists and antagonists, and deficient equilibrium reactions. [4] As a result of these difficulties, children with CP often exhibit a toe-walking gait pattern. Cerebral palsy can affect various limbs which each create a different disturbance in the child's gait pattern.[1] When one limb is involved it is referred to as monoplegic CP. Hemiplegic CP occurs when the upper and lower extremity on one side of the body is affected, and when bilateral lower extremities are involved it is referred to as paraplegic CP. If all four limbs are involved it is termed quadriplegic CP; however, if the lower extremities are involved to a greater degree than the upper extremities it is referred to as diplegic CP. There are also several forms of CP based on the type of tone exhibited by the child, the most common forms being spastic and dyskinetic (athetosis).[1] Spastic CP results in increased tone or contractions of the muscles causing the child to have stiff and awkward movements. Athetosis is a common form of dyskinetic CP, which is characterized by slow, irregular, twisting movements. Other forms of dyskinetic CP include dystonia, chorieform, and ballismus. Specific descriptions of the children's gait patterns associated with the most common types of CP are listed in the following table.

Table 1. Common types of cerebral palsy, characteristics, and resulting gait pattern.[1]

Common Types of Cerebral Palsy	Characteristics	Gait Pattern
1. Spastic Diplegia	• Quadriplegia, UE involvement is mild • Most common • Fixed lesion in motor portion of cerebral cortex	• Hips flexed during stance • Limited, asymmetric pelvic tilt • Excessive adduction and IR of hip • Unable to extend knee at terminal stance and initial contact • To compensate for decrease lower body mobility they shift weight and maintain balance through excessive upper body movement • Feet are positioned in valgus or a narrow BOS in equinus
2. Spastic Hemiplegia	• UE and LE on one side of body involved	• Asymmetric gait pattern • Body weight mostly on uninvolved leg • Shifting weight to involved lower extremity is short and incomplete • Arm swing only on uninvolved side • Lower extremity fluctuates between stiff in extension and mobile in flexion
3. Athetosis	• Intermittent tension in trunk or extremities • Variety of uninhibited movement patterns • Involvement in basal ganglia	• Underlying low postural tone, fluctuating to high tone • Lower extremity lifted into flexion and placed down into stance with extension, adduction, internal rotation and plantarflexion • Hips stay flexed and spine is hyperextended

Neurodevelopmental techniques (NDT), neurosurgical interventions (selective dorsal rhizotomies and implantation of spinal cord stimulators), orthopedic surgeries (muscle transfers, heel cord lengthening, serial casting) and orthotics are just a few of the numerous treatment options available to facilitate the gait training of children with CP. Neuromuscular Electrical Stimulation (NMES) has recently become a common method used to improve the child with CP's gait pattern, however, the majority of research in this area has been completed on adults.[5] NMES is the process of activating muscle tissue through an intact nervous system via electrical current.[6] Using NMES on children differs from adults because of their continuing growth and development, as well as the child's level of tolerance, cooperation and motivation. The ability to tolerate procedures varies with the child's level of maturity and intelligence.[7] Tolerance is important to consider when using NMES with children because it can cause unusual and possibly uncomfortable sensations for the child.

I chose to study the use of NMES in the gait training of children with CP for several reasons. Due to the large population of children with CP, requiring treatment from a physical therapist, it is imperative that clinicians be knowledgeable about treatment options available. Secondly, NMES has produced positive results when used in the treatment of adults, and it would be beneficial for the clinician to look specifically at the results of using NMES on children in order to determine if it is a viable treatment option.

The purpose of this literature review is to discuss the mechanism behind NMES, the various forms and effects of NMES, and its effectiveness in the gait training of children with CP. This will be accomplished by first looking at the uses, forms, and characteristics of NMES, including a brief look at the electrophysiology of NMES, as well as some basic parameters. Other topics that will be discussed are how NMES is used to improve a child's gait pattern by affecting a specific aspect of gait the child is lacking. NMES will improve gait by increasing ROM, strength, and motor control. Lastly, studies utilizing NMES for a particular aspect of gait training will be examined for both technique and effectiveness and are discussed in the respective chapters. Chapter VI will summarize the information that has been presented and suggestions for further studies are proposed.

CHAPTER II

BACKGROUND INFORMATION

Uses of NMES

There are several documented protocols for the use of NMES with adults and/or children, designed to facilitate the following: increasing/maintaining ROM, strengthening and maintaining muscle mass, re-educating musculature, facilitating motor control, reducing spasticity temporarily and substituting for an orthosis.[6,8,9] Regarding ambulation, NMES is being used to facilitate the return of muscle function in children with CP.[9] This is accomplished by using a program designed to counter the effects of disuse atrophy and spasticity, which interfere with the child's ability to ambulate. The role of NMES in gait training of children with CP will be discussed in greater detail in the following chapters.

Theoretical Foundations of NMES

There are several proposed theories for the use of NMES, the following two theories[4] are focused on the facilitation of gait. Comeaux et al.[4] proposed that NMES is beneficial in promoting the phenomenon of reciprocal inhibition. With CP, frequently the tibialis anterior and the gastrocnemius muscles are simultaneously activated rather than acting as an agonist-antagonist pair. By applying electrical stimulation to either one or both of the muscles it is thought that the co-activation pattern can be diminished. Comeaux et al.[4] also proposed that NMES is effective because it provides the child with proprioceptive feedback associated with "normal" movement of muscles, thus facilitating motor learning. Since many children with CP have never experienced voluntary control or appropriate timing of muscle contractions as a result of the neurologic abnormalities in their brain normal muscle movement is inhibited. NMES can allow children to experience what a normal contraction feels like and gain more voluntary control over their muscle contractions.

Electrophysiology and Mechanism of NMES

Understanding how NMES affects muscles and nerves is fundamental to utilizing it for treatment. NMES uses an externally applied current to produce a reaction in excitable tissues.[10] Excitable tissues are defined as those that are able to discharge an action potential, and include muscle and nerve.[6] The stimulator directs a flow of electrons, or electrical current, through two main conducting mediums of the body, ionic fluids and nerves.[5] Electrical current is able to cause an involuntary muscle contraction of innervated skeletal muscle by causing an action potential in the nerve. An action potential is the process by which the nerve's membrane allows the passage of specific ions, which diffuse down their concentration gradients, causing currents to flow in completed circuits resulting in muscle contraction.[9] This process is described in greater detail in the following paragraph. The nerve is more excitable than muscle, and is therefore the primary target for the electrical current.[5]

Prior to activation of an action potential, the resting membrane potential is – 60mV due to differences in concentrations of the cellular ions sodium (Na+) and potassium (K+) across the cellular membrane. The current needs to be adequate to depolarize the nerve causing a reversal in permeability of the membrane. This results in an exchange of ions and an overall increase in resting cell membrane potential. The action potential moves down the nerve to the motor end plate and allows calcuim (Ca+) to be released. Without Ca+ present, the myosin heads are prevented from binding to actin by the tropomyosin proteins covering the actin binding sites. When Ca+ is present it binds to troponin, which in turn, allows tropomyosin to uncover the binding sites for actin and myosin.[11] Once actin and myosin are bound together, cross-bridge shorting (overlap of the shortening filaments) and muscle contractions occur.[5,11]

General characteristics/parameters of NMES

Basic parameters for NMES will be presented in this section, with a more detailed description of protocol parameters will be provided in the following sections. There are two key requirements in utilizing NMES:

1. Current must be balanced in terms of polarity.
2. There must be sufficient charge to depolarize the motor nerve and cause an action potential.[5]

The most important consideration in selecting parameters for NMES is that it is provided in a manner that is tolerable for the child. There are several aspects of NMES that can be controlled to achieve a tolerable level of stimulation including using pulsed current.[5] Thirty to fifty isolated pulses of current per second is usually more comfortable than a solid stream of current for the child. Intensity varies with the effect desired from the treatment and what is tolerable to the child. Reed[5] contended it is important to keep in mind that a shorter duration is usually used with higher intensities and as intensity increases, duration is decreased. Gradually increasing, or ramping, to peak intensities will avoid causing abrupt contractions, which may interfere with the desired motor effects. Providing electrical stimulation with an on/off cycle will help decrease muscle fatigue and increase comfort for the patient.

Fatigue is a greater concern when utilizing NMES to cause a muscle contraction than it is with voluntary muscle contraction. This is due to the manner and type of muscle fibers that are contracted. During normal voluntary muscle contraction, the motor units are fired asynchronously, while NMES contracts all the motor units simultaneously.[5,9,10] During a normal muscle contraction, small, slow motor units fire first and continue with a lower intermittent firing rate. NMES will result in the excitation of the large, fast motor units before smaller ones and with a constant, higher firing rate. The following table summarizes the differences between voluntary and electrically induced muscle contraction.[5,9,10]

Table 2. Comparison of voluntary muscle contraction vs. electrical stimulation.

Voluntary	**Electrical Stimulation**
• Type I muscle fiber contraction precedes Type II • Asynchronous depolarization • Non-fatiguing • Intermittent, lower firing rates	• Type II muscle fiber contraction precedes Type I • Synchronous depolarization • Fatiguing • Constant, higher firing rate

There are several methods of electrode placement including over the muscle belly of the targeted muscle and acupuncture points.[12] Determining the best method of electrode placement is usually on a trial and error basis to find the placement that results in the most effective muscle contraction. Usually the active electrode is placed over the targeted muscle's motor point, while the dispersive electrode is placed at a remote spot away from the active electrode.[5]

Forms of NMES

There are several forms of NMES that can be used in treatment of children with CP: Functional Electrical Stimulation (FES),[2,5,9,12,13,15] Percutaneous Electrical Stimulation (PES),[14,16] Therapeutic Electrical Stimulation (TES),[17,18] and Electromagnetic Biofeedback (EMG)[6,19,21] The basic rationale and application method will be discussed for each of these forms of NMES in the following paragraphs.

FES is defined as the coordinated stimulation of several muscles to provide a purposeful, goal-directed movement that allows engagement in functional activity.[15] The ultimate goal of FES is to increase the patient's strength, stability and motor control enough to reduce their dependence on the external control provided by FES.[6] FES is applied to weak muscles to increase strength and stability, and in some instances, eliminate the need for a brace or orthotic.[9,15]

According to Gersh[9], the most common use of FES as an orthotic is for facilitation of the ankle dorsiflexors during the swing phase of gait. Liberman, et al.[2] studied FES used to assist in ankle dorsiflexion during the swing phase of gait with hemiplegic patients. He found the FES increased torque output of the ankle dorsiflexors and improved their gait pattern. FES has also been applied to the gluteals and/or quadriceps to increase stability during stance phase of gait. Mulcahey and Betz[15] reported when level of function utilizing FES was compared to function with a knee-ankle-foot orthosis (KAFO), utilizing the Functional Standing Test, FES was found to be at least comparable to function with a KAFO and in some cases, better than function with a KAFO.

FES is also used as a locomotion device, to treat contractures and spinal curvatures, and to reduce joint subluxation in flaccid paralysis.[5,9,12] This is generally accomplished by strengthening atrophied muscle through increasing the load on the muscle, promoting muscle re-education by enhancing the proprioceptive feedback received through muscle movement, and managing spasticity through reflex inhibition. There is evidence that gains made with the use of FES, in some situations, are maintained after the FES has been discontinued. These studies will be examined further in following chapters.

FES is applied to motor points of targeted muscles with surface electrodes. The size of the electrode used for stimulation is generally based on the size of the targeted musculature.[9] Larger electrodes are used over a larger muscle or group of muscles, while small electrodes are used when individual muscle stimulation is desired.

Percutaneous Electrical Stimulation (PES) is actually a form of FES. The difference between the two is that FES is applied through surface electrodes, while PES involves surgically implanting indwelling electrodes into selected musculature.[13,16] As many as 8 muscles in each lower extremity can be implanted with electrodes. This allows for 16 channels of electrical stimulation to provide precise stimulation and control of lower extremity movements. Having the electrodes implanted eliminates the time needed to place electrodes and the numerous lead wires daily. Implanted electrodes make PES a more permanent therapeutic intervention. PES is believed to assist the child in a more functional gait pattern by activating the appropriate muscles with more normal muscle sequencing.[16] Bertoti, et al.[16] claimed the use and rationale behind treatment with PES are supported by the current motor learning theory. According to this theory, producing and controlling muscle forces at the appropriate time is to be more important for establishing properly coordinated movement than treating the influences of spasticity or abnormal tone alone.

A third form of NMES is a new form of stimulation being used to promote muscle growth called Therapeutic Electrical Stimulation (TES).[17] TES is a sub-threshold stimulation applied to targeted musculature for 8 to 12 hours while the child is sleeping. The rationale behind applying the stimulation during sleep is that the electrical stimulation causes an increase in blood flow during a time when there is a large amount of trophic hormone secretion.[17] Some of the benefits of TES are that it is non-invasive, convenient, applied during "uncommitted" time, cost effective, and is suitable for home use.[14,18] The benefit of TES specific to gait training of children with CP is the potential strengthening of lower extremity musculature. Pape, et al.[18] studied the application of low intensity electrical stimulation applied to children's non-spastic, antagonistic lower extremity musculature for 9 hours per night for the duration of 6 months. Pape, et al.[18] stated that stimulation was applied at night because neuromuscular growth and repair are known to occur during sleep. The children were evaluated initially with the Peabody Developmental Motor Scale (PDMS) and the parents were instructed in TES application. After 6 months the children had statistically significant increases in their PDMS scores in total gross motor, locomotor and receipt/propulsion skills. The children were able to voluntarily dorsiflex their ankles and their parents reported the children exhibited decreased spasticity. During the next 6 months without TES treatment, there was a uniform loss in scores noted. When TES was started again, the scores increased significantly.

The fourth form of NMES described for use in the gait training of children with CP is electromyographic biofeedback (EMG). Nelson and Currier[6] stated, "EMG refers to the use of appropriate instrumentation to tranduce muscle potentials into visual cues for the purpose of increasing or decreasing voluntary activity." Surface electrodes are applied to the skin over the muscle group that is being targeted. The electrodes pick up the potentials that are then amplified and processed by the instrumentation. The muscle potentials are then converted to a digital value displayed to the patient by light, sound or both.[6] Children with CP are able to re-educate their muscles through the use of feedback, which provides the sensory information he or she does not receive. This information helps the children to increase their level of motor control.[19] This method is especially helpful when working with children, as the biofeedback signals promote the learning of appropriate motor plans without the child having to understand the full mechanism behind moving his/her extremity.[20] Flodmark[21] stated, "Normally, the precise control of load and position of the leg depends on proprioception sensory stimulation, continuous and immediate feedback of amplitude and rate of movement. Verbal feedback is neither continuous nor immediate and therefore correlates poorly with proproceptive feedback."[21] Hence, biofeedback allows for immediate modification of abnormal movements of the extremities, which is necessary to initiate proper proprioception and coordinated movements.

Precautions and Contraindications

There is little literature published on specific precautions or contraindications to using NMES with children.[5] However, precautions and contraindications have been extensively studied and published for the use of NMES with adults. These precautions and contraindications have been generally accepted for the use of NMES with children as well. Some of the specific concerns being studied regarding the use of NMES with children will be further discussed in Chapter VI. General precautions are recommended in the use of electrotherapy with epilepsy and decreased sensation.[5,12] Contraindications to electrotherapy include stimulating over an active area of cancer, over the carotid sinus or laryngeal area, across or through the thorax, over diseased skin, during acute danger of hemorrhage or in the area of a thromboembolism.

CHAPTER III

IMPROVING GAIT BY INCREASING ROM

Children with CP often exhibit abnormal gait patterns secondary to decreased range of motion (ROM) in the lower extremity joints, especially in the ankle.[1,4,5,9,23] Children with CP often have limitations in dorsiflexion secondary to spasticity affecting their plantarflexors. They also exhibit limited knee flexion or extension resulting from an inadequate length of quadriceps or hamstring musculature.[1] Tight hip musculature resulting in limited hip extension, abduction and external rotation is also common in children with CP. One important component of gait affected by the decreased ankle ROM is the ability to achieve heel strike.[4] From neutral, the ankle joint needs to have at least 20 degrees of dorsiflexion and 30-50 degrees of plantarflexion to achieve a normal gait pattern.[22]

Brown et al.[23] proposed that inappropriate development of the triceps surae muscle produces the decreased ROM that children with CP demonstrate. Brown, et al.[23] also contended that children with CP have not received the appropriate stretching on the triceps surae, which normally occurs when the child crawls, stands and walks, and this results in a lack normal ankle ROM. Comeaux et al.[4] hypothesized children with CP display a lack of ankle ROM secondary to an imbalance in the normal agonist/antagonist muscle relationship between the gastrocnemius and tibialis anterior due to spasticity. Spasticity is increased tone or contractions of muscle causing stiff and awkward movements.[24] These authors concluded this creates the "toe-walking" or "foot-flat, crouched gait" commonly seen in the gait patterns of children with CP. The spastic antagonist is usually in a state of contraction or fluctuating high tone. Spasticity may also inhibit a weak agonist, which would prevent the child from using the lower extremity appropriately while ambulating.[9] The weak muscle often will also become lengthened in response to the shortened position of the antagonist muscle.

NMES is used to inhibit the spastic muscle in attempt to restore the balance between the antagonist and agonist musculature, thus allowing normal function.[9] It also is used to stretch the shortened muscle by stimulating the muscles to contract through their available ROM, or to strengthen the weakened agonist, which will be discussed in chapter four.

According to Gersh,[9] NMES is ideal to use in conjunction with active ROM exercises because of its cyclic, repetitive nature. In order to lengthen the muscle, NMES is used to provide a prolonged stretching force, which is not as easy to perform manually.[25] There are two traditional options used when applying NMES to increase ROM in an effort to improve gait. The first method involves stimulating the prime mover against gravity.[5] When the stimulation is in its "off" cycle, gravity will return the limb to neutral. Gradually increasing the electrical current, or ramping, is recommended to prevent the limb from falling down too hard and possibly causing discomfort to the child. The other option is to move the limb through its ROM in a gravity-eliminated position.[5] In this case, stimulation would need to be applied to both the agonist and antagonist alternately to compensate for the elimination of gravity.

Several studies[4,23,26,27,28,29,30] have been conducted to examine the effectiveness of using various forms of NMES to increase ROM. Barry[26] studied using NMES to provide a stretch to the plantarflexors in order to increase ROM and thereby allowing the children to have a more functional gait pattern. Ten pairs of children with hemiplegic CP participated in the study. One group of children received electrical stimulation to the tibialis anterior musculature, 1 hour daily for 35 days. The other group did not receive any electrical stimulation. The results showed increased dorsiflexion and muscle strength for the group that received electrical stimulation. Barry[26] concluded that electrical stimulation could prevent deterioration in ROM. However, the increase in dorsiflexion and muscle strength did not carry-over to cause any significant improvement in the children's gait patterns.

Hazlewood et al.[23] found similar results when electrical stimulation was applied to 20 children with hemiplegic CP. The stimulation was applied to the children's dorsiflexors with enough stimulation to cause dorsiflexion of the ankle to just under the limit of the child's passive range of motion (PROM). Treatment resulted in an average of 0.88-cm increase in gastrocnemius length. There was a significant increase (40-60%) in passive dorsiflexion when the knee was extended. The children also demonstrated a significant increase in active dorsiflexion when sitting upright. However, the children did not show a significant increase in ambulatory function.

Pease[28] completed a case study designed to evaluate the use of functional electrical stimulation (FES) to increase joint ROM involving a twenty-six year old man with familial spastic paraparesis. The symptoms caused by this man's condition were similar to the type of symptoms children with spastic CP suffer from; therefore the treatment effects were comparable. This patient's ROM was impaired because spastic tone impeded joint movement throughout both lower extremities. The patient had undergone several unsuccessful treatments prior to participating in the study including Baclofen, coordination exercises, physical therapist-assisted ROM and strengthening exercises. The initial evaluation revealed bilateral hip flexion contractures, increased tone in lower extremities and adductor scissoring. The patient ambulated with a dysfunctional gait pattern. FES was applied to the quadriceps and dorsiflexor musculature in attempt to improve overall muscle physiology and to decrease spasticity. The intensity was set to cause trace muscle contractions. The other parameters were set at 2500 Hz with a 2 μs pulse width for 8 seconds on and 5 seconds off. The patient received FES 2-3 times a week for 3 months with stretching exercises completed on the alternate days. The patient showed significant improvement in his right hip and knee extension during the stance phase of gait and improved symmetry of his gait pattern. Gait analysis showed a 26% increase in velocity of ambulation, improved cadence and improved step length on the left. The patient stated that coworkers had commented on a noticeable improvement in gait. Five years later the improvement in his ambulation had been maintained.

When clinicians choose to use NMES to increase ROM controversy usually arises over which muscle group should be stimulated.[4,29,30] Traditionally, NMES is applied to the ankle dorsiflexors, and it would appear to be the logical choice considering the goal of treatment is to increase ankle dorsiflexion. Gracian et al.[29] looked at the effects of using FES to stimulate the peroneal nerve innervating the tibialis anterior. One hundred and twenty children with CP received stimulation during ambulation. Positive effects on movement patterns at the hip and knee including decreased internal rotation, adduction at the hip and decreased knee hyperextension were found. However, the authors found that FES could not effectively be applied to children with severe valgus of the foot or with clinical signs of hypotonia.

Dubowitz et al.[30] conducted a study applying electrical stimulation to the tibialis anterior to increase muscle performance. Two children with hemiplegic CP received electrical stimulation for 1 hour, 3 times a day. After a few months of treatment, the children exhibited improvements in motor performance and gait. Objective measurements showed increases in maximum volume contraction of ankle dorsiflexors after electrical stimulation had been applied.

Some researchers and clinicians believe the ankle plantarflexors should be the point of stimulation. It is questioned whether it would be effective to stimulate the spastic musculature, which is most commonly the ankle plantarflexors. It is thought to do so would only increase the spastic tone. According to Comeaux et al.[4] applying NMES to plantarflexors may modify spasticity and the contraction pattern between the gastrocnemius and tibialis anterior, actually reducing spasticity. Kathleen Kolb[27] supported stimulating the ankle plantarflexors and asserted that, "the ankle plantarflexors play a far more important role in stance stability, energy conservation, and forward shift of the center of gravity in gait than do the dorsiflexors." A study conducted by Comeaux et al.[4] found the following positive effects from stimulating the spastic gastrocnemius musculature:

1. Interruption of the constant spastic state of the muscle through the on and off cycle

2. Creation of a reciprocal inhibition of the tibialis anterior, which would result in interruption of the co-activation of the tibialis anterior and gastrocnemius
3. Provision of proprioceptive input for timing of gastrocnemius contraction
4. Promotion of ankle musculature strength
5. Facilitation of prolonged stance phase on stimulated side and therefore enhanced learning to shift weight to the other lower extremity
6. Promotion of normal step lengths
7. Facilitation of the passive elongation of the dorsiflexion musculature during midstance/heel off as the stance time increases

Comeaux et al.[4] studied the ankle ROM of children with CP on four levels: before treatment with NMES, after treatment consisting of stimulation of the gastrocnemius, after stimulation of both the gastrocnemius and tibialis anterior, and eight weeks after the stimulation had been discontinued. The children were required to be able to ambulate up and down 25 steps without the use of orthosis in order to participate in the study. The intensity of the NMES was gradually increased until a visible contraction had been achieved and was held for 15 minutes daily. Data showed statically significant differences in ankle dorsiflexion during gait when NMES was used. Specifically, there was a 4-degree increase in mean ankle ROM when NMES was applied to the gastrocnemius only. There were similar increases found after stimulation of the gastrocnemius and tibialis anterior together. The authors[4] of the study concluded that NMES had a significant, positive effect on ankle ROM. However, it does not seem to matter whether the gastrocnemius or the gastrocnemius and tibialis anterior were stimulated, both methods produce similar results.

CHAPTER IV

IMPROVING GAIT BY INCREASING STRENGTH

Cerebral palsy (CP) often causes a weakness in musculature, which results in a variety of gait disturbances. Children with CP often exhibit slower walking velocities and increased mechanical energy costs.[31]

A strong relationship between joint specific measurements of lower extremity strength and walking parameters has been found in adults with hemiplegia. Kramer and Mac Phail[31] found that the strength of knee extensors in the involved lower extremity was the primary determinant of walking speed. Unfortunately, similar studies focusing on strengthening musculature and its effect on ambulation are few in number. McCubbin and Shasby[32] concluded the reason clinicians tend to avoid or overlook strengthening programs for children with CP is due to the lack of scientific studies and literature on muscle strengthening for children with CP. Another reason could be the assumption that intense voluntary contractions may lead to increased spasticity and additional abnormal reactions. In contrast to that assumption, McCubbin and Shasby[32] found strengthening exercises completed by children with CP over a 6-week period did not cause any adverse reactions. Carmick[33] also stated she did not feel spasticity had increased when children with CP underwent strengthening exercises during her studies.

There are several options available to clinicians wanting to implement a strengthening program to improve gait in children with CP such as traditional strengthening techniques and NMES.[5,8,10,16,31,33,34,35] One theory supporting the use of NMES for muscle strengthening focuses on the concept that in order increase muscle strength, a greater than normal demand must be placed on the targeted musculature.[10,34,35] During traditional strengthening techniques, resistance is applied to the targeted muscle causing an increased demand on the muscle which then creates a greater contractile force. NMES causes muscle strengthening in a similar fashion, by increasing the external load on the muscle. Reed[5] supported this theory noting, "The analog for NMES is high intensity stimulation to induce high force contractions against a high resistance (e.g., isometric contractions), applied on a regular basis (e.g., three to five times per week)." A second theory attributes the strengthening properties of NMES to the fact that it targets and trains type II muscle fibers more effectively than voluntary exercise, as discussed previously in Chapter 2.[10,34] De Luca[35] described the potential of electrical stimulation to strengthen the muscle through activating type II fibers as the muscle's "untapped potential." This phenomenon has to do with the firing rates of the two types of muscle fibers. With a voluntary muscle contraction, type I muscle fibers are activated first at a lower firing rate, then type II muscle fibers are recruited at the same firing rate. This is soon followed by an increase in type I muscle fibers firing rate, however Type II muscle fibers do not increase their firing rates. DeLuca hypothesized that the type II muscle fibers are not firing at their quickest rate, therefore not creating the maximum force possible. By using NMES to target type II muscle fibers, we are able to tap into the unused force thus causing a greater muscle contraction.

There are several muscle groups that could be targeted for NMES strengthening. Carmick[36] suggested, when choosing which muscle group to stimulate, clinicians should take into account which muscle groups appear to be weak with standard muscle testing, if it is possible, and functional strength testing, as well as identifying areas of gait that are difficult for the child. The following table summarizes which muscle groups are commonly stimulated for specific subtasks of gait.[11]

Table 3. Muscle groups commonly stimulated to facilitate certain subtasks of gait.[11]

Subtask of Gait	Muscle Group Stimulated	Side of Body Stimulated
• Stable stance	• Gluteus maximus • Quadricepsfemoris • Gastrocnemius	• Bilateral
• Unilateral limb loading	• Gluteus maximus and medius • Gastrocnemius	• Weightbearing side
• Unweighting and advancing of contralateral LE (in conjunction with unilateral limbloading	• Quadricepsfemoris • Anterior tibialis	• Non-weightbearing side
• Weight shift to forward limb with stability and proper limb placement	• Gluteus maximus • Quadriceps femoris	• Non-weightbearing side

The knee extensors play an important role in ambulation by supporting the child's body weight during stance, and are commonly weak in children with CP.[31] This muscle group works eccentrically during weight acceptance and concentrically during mid-stance. Kramer and MacPhail[31] stated that inadequate knee extensor muscle strength might contribute to the difficulty children with CP have during standing, walking, running and jumping. The ankle plantarflexors are a second group of muscles commonly targeted for strengthening with NMES. The plantarflexors are considered a major postural muscle of the body and contribute to 2/3 of the power necessary for ambulation.[33] The plantarflexors also help conserve energy by contributing to knee and ankle stability. In a case of normal development, the plantarflexors are much stronger than the dorsiflexors.[33] It is a common misconception that this holds true in children with CP, most likely due to the plantarflexed position of the lower extremities exhibited by many children with CP. In fact, the farther the ankle is brought into plantarflexion, the weaker the plantarflexors become due to the decreased lever-arm force vector. Carmick[33] hypothesized children with CP toe-walk as a result of this weakness. The children are able to walk on their toes by bending their knees and bringing themselves forward, utilizing the ankle dorsiflexors for support. The general parameters used when NMES is used to correct these weaknesses are presented in the following paragraph.

General parameters when using NMES for muscle strengthening include a frequency of 30 to 50 Hz with the maximum amount of intensity tolerable using a 1:3 on-off cycle.[5] It is recommended to complete low repetitions of strengthening exercises while high-force electrical stimulation is applied, 3-5 times a week in order to avoid over-fatiguing the musculature, yet still strengthening. Specific parameters used by researchers will be presented with each study.

Kramer and MacPhail[31] conducted a study to evaluate the importance of knee extensor strength and the relationship to ambulation potential. Seventeen adolescents with mild CP participated in this study. Each patient underwent an isokinetic strength test on a Kin-Com machine and an Energy Expenditure Index (EEI) test on 2 occasions, each separated by 7 days. Each patient had 4 practice runs and then 2 maximal effort cycles of knee flexion/extension that were used in the data analysis. The EEI test examined how much walking speed effects the heart rate at a patient-selected walking speed. The lower the EEI, the more efficient the patient's gait pattern. Five electrodes were secured to the patient to monitor the heart rate during 2, three-minute walks (one at a comfortable speed, the second at a fast pace). Each patient's gross motor ability was also evaluated using the standing, walking, running, and jumping components of the Gross Motor Function Measure (GMFM). Knee extensor strength was found to be significantly related to walking efficiency and gross motor ability, while the knee flexion strength was not. The EEI test found that knee extensor strength was very important for energy efficient walking. The results of this study supported not only the importance of knee extensors in ambulation, but also the need to include strengthening of the extensors in the gait training of children with CP.

Bertoti et al.[6] conducted a study with two 6 year-old children with spastic, diplegic CP, which supported the benefits of strengthening knee extensors with NMES.[6] The children presented with a crouched stance and exhibited excessive hip and knee flexion, a narrow base of support (BOS), decreased step-length, and absent knee extension at terminal swing during gait. The children underwent evaluations and muscles identified as having improper timing or weakness were implanted with percutaneous electrical stimulation (PES) electrodes. These muscles included the gluteus maximus, vastus lateralis and medialis. The stimulation was set at 20 mA, pulsed 1 to 100 μsec, in a 1:2.5 on/off cycle delivered through a microchip placed in the child's shoes or with a thumb switch. The children received PES along with exercise and gait programs for 15 min, 2 times a day, 5 days a week until a re-evaluation was thought to be necessary. Both children showed an increase in lower extremity ROM, increase in step length and a decreased BOS after treatment. The children also showed a gross motor improvement in the ability to stop, start, and change directions with decreased falls during ambulation.

Another treatment option is to apply NMES to both the knee extensors and ankle dorsiflexors simultaneously in order to increase their strength. Comeaux et al.[4] studied 52 children with spastic, diplegic CP in which therapeutic electrical stimulation (TES) was applied, while the child slept at night, through surface electrodes placed over the anterior tibialis and quadriceps femoris musculature. The children's parents were instructed on the proper application of electrodes and electrical stimulation and also recorded the children's periods of sleep, duration of stimulation, functional changes and any problems that occurred during treatment. The TES was set at 300μsec at 35-45 Hz with a 1:1 on/off cycle. The intensity was set at just above sensory threshold with no active muscle contraction noted. The assessments, using the Progressive Ambulation Scale (PAS), were carried out at baseline, 6, and 12 months. The PAS is a ten point descriptive ordinal scale, which was developed for the study, which evaluates children's gross motor functional skills in the following ten categories:

1. Independent sitting
2. Crawling
3. Balancing in tall kneeling
4. Stand with support
5. Walker use
6. Crutch use
7. Cane use
8. Independent household ambulation
9. Walking aid for distance
10. Independent walking

During the initial evaluation, each child was put into one of 3 groups: mild, moderate or severe involvement. In order to be classified as mild, the child had to have a score of 10 on the PAS and be described as an independent ambulator with or without bracing. Children who were placed in the mild category also were scored on the balance and locomotor subsections of the Peabody Developmental Motor Scale (PDMS). The children in the moderate category scored between 5 and 9 points on the PAS and were able to ambulate only with an assistive device and bracing. Children in the severe category scored between 1 and 5 points on the PAS and were either not ambulatory or were only household ambulators with walking aids.

Following treatment, children classified as having mild involvement had gained new skills (jumping, balancing on one foot, and walking backward and sideways) as evidenced by an increase in PDMS scores and parental reports.[4] Comparisons between baseline, 6 and 12-month assessments showed a statistically significant improvement in locomotor and balance skills. The children's parents reported decreased falling, increased endurance, and increased ability to transition to standing independently. Many children in the mild category decreased their use of orthosis to only inserts or nothing at all. The children in the moderate category showed mean score improvements on the PAS scores. The children progressed from walker use to crutch or cane use. Twenty-eight percent of the children became independent ambulators, advancing them from the moderate to mild category. The children also improved posture and balance for independent sitting. They were able to use a more controlled 4-point reciprocal crawling pattern and maintain a tall kneeling position. The children in the severe category showed improvement by increasing their sitting balance and improving their reciprocal crawling pattern, and a decrease in lower extremity spasticity was also noted. However, none of the children in the severe category improved enough to progress to the moderate category. In general, the parents noted the children exhibited increased self-confidence, risk-taking and cooperation. The authors concluded that TES was effective for increasing muscle strength and decreasing spasticity. Another benefit of TES was the direct patient and parent involvement in treatment.

There is also documented research studying the effects of NMES application on the ankle plantarflexors to increase strength. Carmick[8] completed a study in which NMES was applied to the lower extremities of 3 children with hemiplegic CP, ages 1.6, 6.7, and 10.0. Each child received electrical stimulation to 4 different muscle group combinations. First NMES was applied to only the anterior tibialis for 5 weeks. The NMES appeared to have no effect on gait or PROM after the 5-week session. Second, the children received NMES to the gastrocnemius and anterior tibialis alternately for 5 weeks. This resulted in the ability to place the foot in a plantigrade position and intermittently improved gait pattern. However, ROM did not improve and little carry-over was noted. In the third trial, the gastrocnemius was solely stimulated for a few weeks and then the anterior tibialis was added. This did not result in change in the child's ambulation ability. The fourth method utilized stimulation solely of the gastrocnemius. This resulted in a significant improvement in the child's gait pattern and the ability to shift his/her weight. The favorable results of using NMES solely to the gastrocnemius prompted Carmick[33] to complete a second study looking closer at using NMES to increase the strength of the gastrocnemius musculature. In this study 4 children, with varying degrees of CP, were treated with NMES in addition to their physical therapy program.[33]

Case 1: The first subject was a 34-month old girl with spastic diplegia resulting in asymmetrical lower extremity involvement.[33] The child received NMES to her anterior tibialis musculature during functional activities for a 3 month period. The NMES provided some carry-over but it was limited to a day or two after the discontinuation of electrical stimulation. The plantarflexors did, however, appear to have increased strength. For the next 3 months NMES was alternately applied to the anterior tibialis and the plantarflexors. This resulted in an improved heel-strike that occurred more frequently than it had prior to treatment. Then child then received no traditional physical therapy for 6 months. NMES was initially continued at home but the parents discontinued use because the child continued to toe-walk. The child's ankle was then casted in an effort to lengthen the gastrocnemius but this was also discontinued due to a deep wound that formed on the child's foot. The child returned to physical therapy at 48 months of age. At this time, the child received electrical stimulation solely to the gastrocnemius, which immediately resulted in the ability to place her foot in a plantigrade position. Carmick[33] theorized this resulted from an increased load placed on the muscle by the electrical stimulation, which caused an increase in contracting muscle fibers and strength so, the plantarflexors could be used in a more normal manner. The child progressed to the ability to walk barefoot with a strong heel strike for 5 meters before toe-walking returned.

Case 2: The second subject was a child with spastic, diplegic CP resulting in symmetrical lower extremity involvement.[33] The child utilized a hinged AFO for ambulation and presented with a toe-walking gait pattern accompanied by excessive lumbar lordosis, hip flexion, and internal rotation. NMES was applied to bilateral gluteus maximus, triceps surae, lateral hamstrings and external obliques. The child immediately demonstrated plantigrade stance with small, short steps. When stimulation was increased to the triceps surae, an improvement in external rotation and dorsiflexion was noted. As the child's strength increased, the amount of valgus decreased and gait velocity increased.

After 5 months the child was able to ambulate plantigrade while barefoot, even without the NMES.

Case 3: The third subject was a 56 month old girl with quadriplegic CP who had been receiving physical therapy since she was 13 months old.[33] Before NMES was started the child walked with a medium guard, forward on her toes and with her lower extremities in an adducted and internally rotated position. NMES was applied bilaterally to her triceps surae, gluteus maximus, and lateral hamstring musculature. Within one month the child could walk three meters while carrying a toy with both hands. By 59 months, she began walking indoors independently with less frequent falling, and she used a reverse walker and hinged AFO's for outdoor ambulation. At 70 months the child could actively invert/evert and align the foot in a nearly neutral position. Her balance and posture had also improved significantly.

Case 4: The forth subject was a 33-month-old child suffering from ataxia.[33] While this patient did not have CP, he was included in the study because of his difficulty in maintaining his balance, much like a child with CP. The child presented with an ataxic gait pattern and poor balance, which resulted in frequent falling. NMES was applied to the child's left triceps surae and gluteus maximus for 6 treatment sessions. In only 3 months, the child's balance and functional abilities had significantly increased as indicated by a decreased number of falls.

From these studies, Carmick[33] concluded that strengthening of the gastrocnemius improves foot and body posture, gait pattern, balance and energy efficiency.

CHAPTER V

IMPROVING GAIT BY INCREASING MOTOR CONTROL

Children with cerebral palsy (CP) have difficulty controlling their muscle movements.[1] Often there is co-activation of the agonist and antagonist muscle groups, which may lead to a physiological splinting of the limb.[13,23,37] Children with CP particularly have problems during gait with the untimely contraction of the LE musculature which interrupts the normal work/power system that facilitates and provides motivation for a normal walking pattern.[37] Harris[19] suggested children with this disability have motor incoordination problems due to a faulty perceptual system rather than the system of motor control. Sensory stimulation that occurs during motor level stimulation may provide facilitory feedback to motor units, which may enhance motor control and motor learning.[25] The fact that the peripheral nervous system (PNS) and the central nervous system (CNS) are capable of neural plasticity, or adaptation of the nervous system, following a system "insult" such as CP, supports the use of sensory stimulation to enhance motor control.[9] Sensory stimulation encourages the formation of new neural pathways to achieve movements that were lost as a result of the "insult". The theory behind utilizing NMES is to supplement the children's voluntary contraction efforts with simultaneous NMES activation, resulting in contraction, of targeted muscle groups, is that the child will be able to use the resulting visual and kinesthetic information to learn or re-learn a motion.[5]

Several methods and types of NMES are used for muscle re-education.[9] NMES can be applied transcutaneously with enough intensity to create a "light touch" sensation that activates the sensory nerve fibers. NMES may also be used at an intensity that evokes a muscle contraction and provides proprioceptive information from the Golgi Tendon Organ and muscle spindles to the CNS.[9] Electromyographic biofeedback (EMG) is another form of NMES used in muscle re-education and facilitory treatment programs. Most of the studies completed using NMES for muscle re-education have utilized EMG; therefore this chapter will focus on literature involving EMG biofeedback.

Several studies[20,21,37,38,39,40] have been performed that examine the effectiveness of using EMG to increase muscle control and improve the gait patterns of children with CP.. Flodmark[21] studied 7 children with varying diagnoses of spastic diplegia, hemiplegia, and athetosis to assess the effectiveness of EMG in their gait training. A switch was inserted into each child's shoe, which records the number of deviations outside the present knee joint angle, the number of correct weight bearing steps with heel down and total elapsed time. An acoustic signal was set to sound if the child exceeded the targeted angle. The results of the study found that children with diplegic and hemiplegic CP ambulated more correctly than the children with athetosis. Children 1, 3 and 7 (who had primarily motor handicaps) rapidly achieved good results, including the ability to walk 25 meters with an improved gait pattern. Child 2 had a short attention span and tired easily. Children 4, 5, and 6 had inconsistent results from the gait training. The authors of the study found intellectual capacity and motivation to also play a role in the results of training.

Colborne, et al.[37] conducted a study to examine the activity of the triceps surae early in the stance phase of the gait pattern and to test the efficiency of computer-assisted feedback in reducing any untimely activity found. Seven children with hemiplegic CP participated in the study. Targets for muscle activation/deactivation were set on a computer screen, along with timing cues that were controlled by a foot switch and prompted the subject for target levels of activity at appropriate times in the walking cycle. The training resulted in an increased walking velocity, improved stance/swing ratio (indicating increased stance time relative to swing time) and a positive change in ankle work at push-off and in peak ankle power. Ankle dorsiflexion, however, did not increase following training. The authors felt providing a passive stretch and mobilizations of the ankle in addition to the biofeedback training would help increase the children's ankle ROM.

Conrad and Bleck[38] conducted a study to examine the effectiveness of using augmented auditory feedback device to correct dynamic equinus of children with CP.. Six children with spastic CP and two children with idopathic toe walking completed the study. The parents and children were also instructed to use the device at home 1 hour per day for 4 months. The study had the following results: 1) Pedograph: every patient demonstrated heel contact after training, however most only walked a short distance before returning to a toe-walking pattern. 2) PROM of the ankle: each child improved 4-8 degrees. 3) Time/event counter: there was a 90% improvement in total accumulated seconds in the heel down position and a 38% increase in total accumulated number of heel strikes in a 3 minute period. Four children were evaluated from 3 months to 1 year later; 2 of the children had further increases in dorsiflexion by 5 degrees and the other 2 children remained the same.

Four children with hemiplegic CP participated in a study by Seeger et al.[20] examining the use of biofeedback to correct deficient weight bearing on their affected leg. The study resulted in increased weight bearing, with scores above the 95% confidence interval. This increase was maintained during the post-training assessment. Children #3 and #4 had a statistically significant approach to symmetrical weight bearing between the hemiplegic and non-hemiplegic side. They also had an improved heel strike on the hemiplegic leg. A follow up study was completed between 18 – 24 months later and found the gains made in the previous study had not been maintained.[40] The authors[40] felt the children would have benefited from additional training to maintain the learned behavior.

A study conducted by Nash et al.[39] to determine if children with CP could be trained with biofeedback to decrease their spasticity. Three children with spastic diplegic CP participated in the study. Each child underwent 18 weeks of biofeedback training during which time he or she was instructed to move their ankle through it's maximum range of motion. The children's parents were given instructions and equipment to also conduct training at home. The study resulted in an increase in ankle ROM for all 3 children, however t-tests found the results to be significant for only 2 of the children (a 10 degree increase in ROM). There was a high degree of fluctuation in spasticity scores from day to day but the overall level of spasticity decreased after training, again the t-tests found the results to be significant for only 2 of the children.

Skrotzky et al.[41] studied the effectiveness of using EMG feedback on the motor control of the gastrocnemius and anterior tibialis in children with spastic, diplegic CP. The study specifically looked at the change in active range of motion (AROM) of the ankle, time needed for relaxation after a muscle contraction, and the degree of retention after training is completed. The study resulted in an increase in AROM of the ankle in the experimental limb at the end of training period A and a similar increase in the control leg after training period B. The retention period showed that 2 of the subjects (both were moderately involved) retained the improvements in both the experimental and control limbs. Two of the children (both were severely involved) did not retain the improvements gained during training.

CHAPTER VI

CONCLUSION

Through the review of current literature, NMES was found to be an effective method of improving gait function in children with cerebral palsy (CP).[4,8,16,21,28,30,31,33,37,38] This improvement was noted most often when NMES was used in conjunction with actual ambulation.[4,8,16,21,27,28,30,31]

Several studies[4,23,26,27,28,29,30] found NMES to be effective in increasing ankle ROM, however overall it did not carry-over well to ambulation. Results regarding the improvement of gait following electrical stimulation were controversial. Some clinicians[14,26] found no significant increase in ambulation skills after treatment, while others[4,28,30] reported significant improvements. There was also significant support for providing stimulation to the tibialis anterior solely, as well as literature supporting stimulation to only the gastrocnemius muscle.[4,27,29,30] Comeax et al.[4] compared both alternatives and found no significant evidence favoring one or the other. Researchers[21,38,41] recommended implementing gait training techniques in conjunction with NMES in order to increase the likelihood of improving the child's gait pattern.

Several studies[5,10,16,31,33,34,35] found NMES to be effective for strengthening children with CP's musculature, which also carried over into their ambulation skills. Improved skills included an increased step length, dynamic stability and ability to place their foot properly. Some children also exhibited a better BOS and decreased number of falls.

For some children, using EMG to enhance motor control resulted in an increase in ROM, ankle push-off power and symmetrical weight bearing.[4,16,33] Unfortunately, one study[8] did not have positive results. Colborne, et al.[37] felt providing a passive stretch to the ankle musculature and providing additional gait training would enhance the results of using EMG for gait training.

Most authors[5,12,16,22,36] share the belief that determining which muscle group to stimulate depends on the individual patient. It may be helpful to try stimulating several different muscle groups in order to determine which provides the best result for each child. Carmick[36] stated that key factors to consider include the child's areas of muscle weakness and deficits in their ambulatory function.

A small number of the authors[7,32,39] expressed concern about whether the changes seen after treatment are due to the NMES or if they are occurring as a result of the child's ongoing growth and development. In my review of current literature, I was unable to find a study designed to clearly differentiate between the two factors.

While the growing interest of clinicians regarding the use of NMES with children has been prompting more research, there is still a need for more scientific evidence supporting its use. I recommend further research be completed regarding the safety of using NMES with children. It would be beneficial to have scientific evidence concerning the effect of NMES on growing muscle, tendons and bones, as well as the possibility of overworking weak musculature. Further research into the learning component involved in the use of NMES with children, particularly with EMG, would be beneficial. The level of the child's cognition may determine whether NMES will be effective in the gait training of children with CP.

Another area of research I feel would benefit from further investigation is the population type being used for the study. While several authors[4,14,16,20,21,22,26,27,28,29,30,37,38,39,40] made note of which type of CP the child had, few made reference to the child's race, culture or socioeconomic background. I feel it would be beneficial to look into the role these factors may play in the use of NMES, including parent's education level and a particular cultures belief on health care and "healing". These factors could significantly impact the results of using NMES as a therapeutic tool.

I recommend further research be completed regarding the long-term affects of NMES on the gait training of children with CP. Several of the studies[14,16,21,22,26,27,29,30,37,39,40] examined in this literature review only reported results up until the time the study was finished. Only a few authors[4,20,28,38,41] reassessed their patient's 3-6 months after completion of the study. It would be beneficial to have more studies examining the results, not only at 3-6 months, but also periodically for at least five years after the completion of the study. This would allow us to examine the carry-over of the NMES itself, as well as the effect that children's growth spurts might have on the results.

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